CA-AQM: Channel-Aware Active Queue Management for Wireless Networks

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***Abstract*— In a wireless network, data transmission suffers from varied signal strengths and channel bit error rates. To ensure successful packet reception under different channel conditions, automatic bit rate control schemes are implemented to adjust the transmission bit rates based on the perceived channel conditions. This leads to a wireless network with diverse bit rates. On the other hand, TCP is unaware of such *rate diversity* when it performs flow rate control in wireless networks. Experiments show that the throughput of flows in a wireless network are driven by the one with the lowest bit rate, (i.e., the one with the worst channel condition). This does not only lead to low channel utilization, but also fluctuated performance for all flows independent of their individual channel conditions.**

To address this problem, we conduct an optimization-based analytical study of such behavior of TCP. Based on this optimization framework, we present a joint flow control and active queue management solution. The presented channel-aware active queue management (CA-AQM) provides congestion signals for flow control not only based on the queue length but also the channel condition and the transmission bit rate. Theoretical analysis shows that our solution isolates the performance of individual flows with diverse bit rates. Further, it stabilizes the queue lengths and provides a time-fair channel allocation. Test-bed experiments validate our theoretical claims over a multi-rate wireless network testbed.

***Index Terms*— wireless networks, flow control, active queue management, optimization**

I. Introduction

Wireless networks provide ubiquitous access to information and computational resources, and become a popular networking solution in both home, office and public areas such as airport and cafes.

In wireless networks, the signal strength and noise level of wireless channels vary widely, especially in indoor environments, leading to diverse channel bit error rates (BER). In IEEE 802.11, to reduce the BER, the sender can transmit at a lower data rate by using a more resilient modulation scheme. Four different bit rate levels (11, 5.5, 2 and 1Mbps) are defined in IEEE 802.11 standard. Many vendors of client adaptors and access points implement automatic bit rate control scheme in which the sender adaptively changes the bit rate based on the perceived channel conditions. This leads to a wireless network with *rate diversity*, where competing flows within the interference range transmit at different rates.

This paper studies the performance of TCP over such multi-rate wireless networks. Besides the unfairness issue, which are researched extensively in the existing literature, we provide an analytical explanation for the following observations from test-bed experiments.

- Throughput of flows in a wireless network is confined by the ones with the lowest bit rate (i.e., the one with the worst channel condition), leading to low channel utilization.
- If there is one flow suffering from fluctuated channel condition, all flows in the network exhibit highly dynamic behaviors, independent of their individual channel condition which causes instability in their application performance.

To address these issues, we investigate a joint solution of flow control and active queue management. Although several flow control and active queue management schemes have been proposed in the context of wireline networks, the unique physical characteristics of wireless networks pose the following challenges which prevent the verbatim applications of the existing algorithms.

- First, compared with wireline networks where flows only contend at the router that performs flow scheduling (contention in the time domain), the unique characteristics of wireless networks show that, flows also compete for shared channel if they are within the interference ranges of each other (contention in the spatial domain).
- Second, in a wireless network with rate diversity, different users have different views of the wireless channel capacity. Such observation raises the question of how *fairness* criteria should be defined in wireless networks.
- Third, under IEEE 802.11 the achievable channel capacity may vary depending on the number of active users of the wireless networks. This observation prevents the application of previous active queue management schemes which requires the prior knowledge of resource capacity.

To address these challenges, we present a channel-aware active queue management (CAAQM) scheme. CAAQM provides congestion signals for flow control not only based on the queue length but also the channel condition and the transmission bit rate. Theoretical analysis shows that our solution has the following properties.

- *Performance isolation*. The throughput of individual flows only depend on their own channel conditions and BER, but not others as in the case of TCP.

- *Local stability*. The presented joint flow control and active queue management scheme can be modelled as a nonlinear system via a utility-based approach. We show that the system is locally asymptotically stable.
- *Fairness*. At equilibrium, the system achieves proportional fairness in terms of channel time, where the aggregated utility of all flows are maximized.

The remainder of this paper is organized as follows. We first motivate our work by studying the performance issues of TCP over multi-rate wireless networks in Sec. II. Then we present the optimization-based theoretical framework for our flow control scheme in Sec. III and its channel-aware active queue management implementation in Sec. IV. We evaluate our solution in Sec. V. Finally, we discuss related work (Sec. VI) and conclude the paper (Sec. VII).

II. Problem Overview

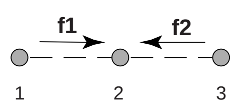


Fig. 1. Network Topology.

We start with an experimental study of TCP performance in a multi-rate wireless network. In the experiment, we set up a three-node wireless network as in Fig. 1. At time instance 0 sec, node 3 establishes a TCP connection (flow 2) to node 2 at a fixed bit rate 11Mbps. Then at time 25 sec, node 1 sends to node 2 (flow 1) with a varied bit rate using TCP. Initially, we manually adjust the bit rate of node 1 at different levels (in the sequence of 11M, 2M, 5.5M, and 1Mbps). Then at time instance 160 sec, we set the bit rate of node 1 to automatic adjustment mode, then move node 1. The observed throughput of both flows and the transmission bit rate of flow 2 are shown in Fig. 2.

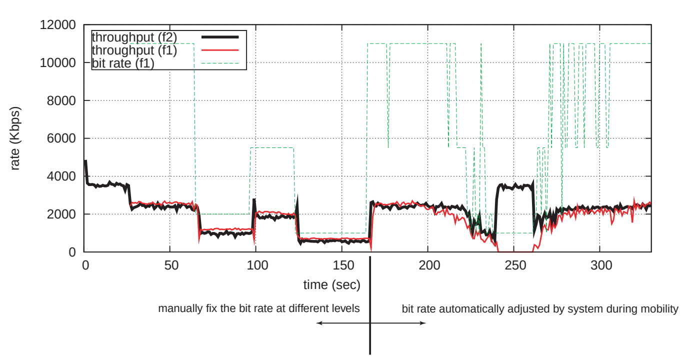


Fig. 2. Instantaneous throughput and bit rate.

From the figure, we have the following observation. (1) The throughput of both TCP flows are affected by the bit rate adjustment of node 1, even though the bit rate of flow 1 remains to be 11bps; (2) When node 1 is mobile, it experiences highly dynamic channel condition, which causes fluctuated transmission bit rate and throughput of flow 1. More importantly, flow 2 also suffers from the same performance instability, even though it is static and enjoys a more consistent and good channel condition; (3) Only during time 240 sec to time 260 sec, when the channel condition of flow 1 is so bad that its RTS signal can not be perceived at node 2 and it is virtually get disconnected, the throughput of flow 2 gets back to its normal value. Experiments on many other topologies also validate our observations.

In summary, the experiment result shows that *one bad connection will drive down the performance of all TCP flows in a multi-rate wireless network* without proper scheduling and/or queue management support. And this observation motivates us to study the efficiency and stability of flow control mechanisms over multi-rate wireless networks. It is worth noting that besides flow control, the scheduling mechanism [1], [2] could also be used to improve the TCP performance in this scenario. Yet residing at a higher-level of the network stack, solutions based on flow control and queue management require less support from the infrastructure and are more flexible in implementation and deployment.

III. An Optimization-based Flow Control for Multi-Rate Wireless Network

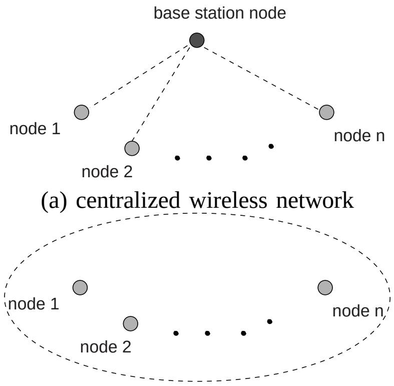
One of the reasons for such deficiency in TCP performance is that TCP *tries to* achieve *throughput fairness* among flows. This is a reasonable concept in wireline networks, where flows which share the same resource –wireline link, have the same transmission bit rates. In multi-rate wireless network, although the flows contend for the same wireless channel resource, they have different bit rates, thus different capacities to utilize the resource. Such observation suggests that we need to reconsider the goal of flow control and resource allocation in multi-rate wireless networks, where the concept of *fairness* is re-defined.

In this section, we present a utility-based nonlinear optimization formulation for the flow control problem in wireless networks. The formulation follows Kelly's congestion control model [3], yet incorporates the unique characteristics of wireless networks [4]. This optimization framework provides an analytical insight to the performance deficiency problem of TCP over multi-rate wireless network, and establishes a theoretical foundation for the active queue management scheme that solves this problem.

A. Problem Formulation

We consider IEEE 802.11 based wireless networks that are deployed in two styles, as shown in Fig. 3. In the centralized wireless network, each wireless node in the wireless network communicates with a base station or an access point (AP) via IEEE 802.11. In the distributed manner, a wireless node communicates with other nodes within the transmission range directly. The wireless nodes in the network may experience diversified signal strengths and channel bit error rates and they can adaptively change their bit rates based on the perceived channel conditions.

Consider a set of flows F in such a wireless network. Let the rate of flow $f \in F$ be x_f and the bit rate of flow f be



(a) centralized wireless network

(b) distributed wireless network

Fig. 3. Two wireless network deployments.

B_f. Then under ideal MAC scheduling as shown in Fig. 4(a), the rates of all flows satisfy the following relation.

$$\sum_{f \in F} \frac{x_f}{B_f} \leq 1 \tag{1}$$

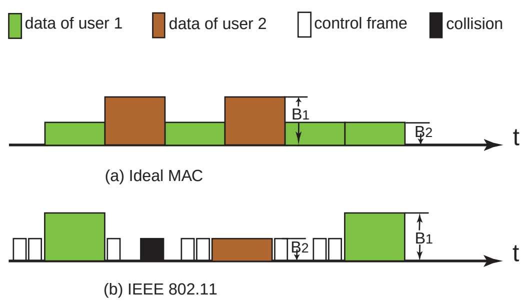


Fig. 4. Channel usage in wireless network.

In Eq. (1), $\frac{x_f}{B_f}$ is the percentage of the channel time that flow f uses. Eq. (1) states that the total percentage of channel time used can not exceed 1.

In practice, channel time used for data transmission can be much less than the ideal case in an IEEE 802.11-based wireless network. As shown in Fig. 4(b) due to the nature of CSMA/CD protocol, besides data frame transmission, wireless channel can be idle, suffer collision, or transmit control frame. Let ρ_{max} be the percentage of channel time used in data transmission (so called maximum channel utilization). Then the condition of flow rates can be written as follows.

$$\sum_{f \in F} \frac{x_f}{B_f} \leq \rho_{max} \tag{2}$$

We proceed to consider the goal of flow control in the multi-rate wireless network. To have a systematic study on the tradeoff between the user fairness and the channel utilization, we adopt a *utility*-based approach [5]. We associate each flow $f \in F$ with a *utility function* $U_f(x_f) : \Re_+ \rightarrow \Re_+$, which represents its degree of satisfaction with rate x_f. Assume that $U_f(\cdot)$ is increasing, strictly concave and continuously differentiable.

We consider the optimization problem to maximize the aggregated utility of all flows. Existing research has established that such an objective would define various notions of fairness and realize different TCP algorithms,when appropriate utility functions are specified. Formally, we formulate the flow control problem in a multi-rate wireless network as the following non-linear optimization problem:

S:

$$\textbf{maximize} \quad \sum_{f \in F} U_f(x_f) \tag{3}$$

$$\textbf{subject to} \quad \sum_{f \in F} \frac{x_f}{B_f} \leq \rho_{max} \tag{4}$$

$$\textbf{over} \quad x_f \geq 0 \tag{5}$$

B. Flow Control Algorithm

We now present the algorithm to solve the above optimization problem **S**, and perform rate control for competing flows in multi-rate wireless networks. The algorithm that we present solves a relaxation of the original **S** problem using a penalty-based approach. The basic idea of this algorithm is as follows. A wireless channel incurs certain *penalties* when heavily loaded. To quantify the penalty, it charges a price ν to each unit channel time usage. A flow f with rate x_f will then be charged for these penalties, quantitatively represented by a flow cost

$$\nu \cdot \frac{x_f}{B_f} \tag{6}$$

Flow f attempts to adjust its rates to maximize its net benefit, which is the difference between its cost $\nu \cdot \frac{x_f}{B_f}$ and its utility $U_f(x_f)$, which is

$$\max_{x_f} \{U_f(x_f) - x_f \cdot \frac{\nu}{B_f}\} \tag{7}$$

Obviously, a unique maximizer x_f exists when

$$\frac{d}{dx_f}(U_f(x_f) - x_f \cdot \frac{\nu}{B_f}) = U_f^{'}(x_f) - \frac{\nu}{B_f} = 0 \tag{8}$$

The flow control algorithm can be represented in the following differential equation:

$$\frac{dt}{x_f(t)} = \gamma\left(1 - \frac{1}{U_f'\big(x_f(t)\big)} \frac{\nu(t)}{B_f}\right) \tag{9}$$

where γ is the step size and $\nu(t)$ is the channel time usage price which is a function of the aggregated channel time requested by all flows, *i.e.*,

$$\nu(t) = \nu(\sum_{f \in F} \frac{x_f(t)}{B_f}) \tag{10}$$

This is an additive-increase, multiplicative-decrease algorithm, where the flow reduces its rate according to its unit flow cost – flow price $\frac{\nu}{B_f}$. The algorithm tries to equalize the flow price $(\frac{\nu}{B_f})$ with a target value $U_f^{'}(x_f)$, where its net benefit is maximized according to Eq. (8).

Now we analyze the properties of the algorithm. Let $\boldsymbol{x} = (x_f, f \in F)$ be the flow rate vector. We first establish the stability of the rate control algorithm given by Eq. (9), and show that it solves a relaxation of the **S** problem, the maximization goal of which is given by

$$\mathcal{V}(\boldsymbol{x}) = \sum_{f \in F} U_f(x_f) - \int_0^{\sum_f x_f/B_f} \nu(z)dz \tag{11}$$

Theorem 1. $\mathcal{V}(\boldsymbol{x})$ is strictly concave. Moreover, it is a Lyapunov function for the system of the differential equation (9). The unique value $\boldsymbol{x}$ that maximizes $\mathcal{V}(\boldsymbol{x})$ is a stable point of the system, to which all trajectories converge.

Proof. Observe that

$$\frac{\partial \mathcal{V}(\boldsymbol{x})}{\partial x_f} = U'_f(x_f) - \frac{\nu\big(\sum_f x_f/B_f\big)}{B_f} \tag{12}$$

Setting these derivatives to zero identifies the maximum. Further

$$\frac{d\mathcal{V}(\boldsymbol{x}(t))}{dt} \tag{13}$$

$$= \sum_{f \in F} \frac{\partial \mathcal{V}(\boldsymbol{x})}{\partial x_f} \cdot \frac{dx_f(t)}{dt} \tag{14}$$

$$= \gamma \sum_{f \in F} U'_f(x_f)\left(1 - \frac{1}{U'_f(x_f)} \cdot \frac{\nu\big(\sum_f x_f/B_f\big)}{B_f}\right)^2 \tag{15}$$

This establishes that $\mathcal{V}(\boldsymbol{x}(t))$ is strictly increasing with t, unless $\boldsymbol{x}(t) = \boldsymbol{x}^*$, the unique $\boldsymbol{x}$ maximizing $\mathcal{V}(\boldsymbol{x})$. The function $\mathcal{V}(x)$ is thus a Lyapunov function for the system Eq. (9), which establishes the result of Theorem 1. □

Now we proceed to study the result of rate allocation at the equilibrium.

Corollary 1. At equilibrium, the rate allocated to flow f is given by $x_f = U_f'^{-1}(\frac{\nu}{B_f})$. When $U_f = \log x_f$, the rates allocated to any two flows $f_i, f_j \in F$ satisfy the proportional relation

$$\frac{x_{f_i}}{B_{f_i}} = \frac{x_{f_j}}{B_{f_j}} = \frac{1}{\nu} \tag{16}$$

This result shows that (1) the rate of flow f only depends on the channel time usage price and its own bit rate. The channel time price does not change with the bit rates of individual flows. Thus the bit rate adjustment of one flow will not affect others' flow rates; (2) at equilibrium, the flow rate allocation follows time fairness, when the utility function takes the special form as $U_f = \log x_f$. This result also provides a theoretical foundation for the notation of time-based fairness [1], [2]. Further, different from existing works that provide time-based fairness in wireless network [1], [2], our approach is distributed and involves no changes to the MAC and network layer.

Such an optimization-based flow control framework has been shown to be closely related to the TCP behavior – the equilibrium structure of TCP solves the utility maximization problem in Internet [6] (with different utility function definition for different TCP versions). Yet compared the TCP dynamics $(\frac{dt}{x_f(t)} = \gamma\big(1 - \frac{1}{U'_f(x_f(t))}\nu(t)\big)$ [3], [6][1]) with the presented flow control algorithm in Eq. (9), we have the following observation that explains the TCP performance anomaly over multi-rate wireless networks. The TCP flows with different bit rates have the same flow price, but different channel time price. Thus although the flow control algorithm of TCP will converge to the solution of utility maximization problem in the wireline network, it fails to do so in the multi-rate wireless network. In order to achieve utility maximization and thus flow fairness, the transmission bit rate has to be considered into the flow price.

IV. Channel-Aware Active Queue Management

A. Algorithm

Our penalty-based rate allocation algorithm presented in Sec. III only solves a *relaxation* of the **S** problem. Clearly, how closely the solution of the relaxed problem matches the solution of the original constrained resource allocation depends on the price. In this section, we present a *price computation algorithm* where the channel time usage prices are computed based on the queue length and the channel condition.

As a penalty, the wireless channel price increases with the load. The question, however, is *how much* the price should increase, or alternatively, what is the relation between the load increase and the price increase, so that the value of the prices lead to the global optimum at equilibrium. In previous work [7], [4], [8] that has attempted to determine such a price, we need to know *how much* the load exceeds the capacity, or *how much* the channel is under-utilized. In wireless networks, however, the achievable channel capacity is not known *a priori*, and the aggregated rate in the wireless channel can be difficult to obtain efficiently (e.g., without message exchange). In our price computation algorithm, we propose to use both channel measurements and queue monitor to infer the relation between the traffic load and the channel capacity. Price increases when the aggregated normalized queue length increases in the wireless network. When queue length is not long enough to accurately monitor its length change, the price is generated based on channel measurement. Formally, Let q_f be the queue length at the sending node of flow f. The price is generated according the following algorithm.

If $q_f \geq Q_{thresh}$
$\nu[t+1] = [\nu[t] + \alpha \sum_{f \in F} \frac{q_f}{B_f}]^+$
else $\nu[t+1] = [\nu[t] + \alpha \frac{x_f - BW_f}{B_f}]^+$

TABLE I

Price computation algorithm

where α is a price adjustment parameter ($\alpha \ll \gamma$), and Q_{thresh} is the threshold above which queue length change can be accurately generated. BW_f is the estimated channel

[1]This equation implicitly assumes that the flows from different wireless nodes share the same congestion signal, which holds for single-hop wireless network. For multi-hop wireless network, this equation may not hold as shown in [4].

capacity from the view point of flow f, which is discussed in detail in the next section.

B. Implementation

We implement our joint flow control and active queue management in the Linux system kernel version 2.6.5. The software architecture is show in Fig. 5.

In this figure, *rate adaptation* (Eq. 9) is implemented at both sender and receiver via four modules, which are responsible for sending(or receiving) data(or feedback flow price) packets, respectively. *price computation* (Tab. I) is implemented as several components at different levels. At the MAC level, the bandwidth estimator measures the achievable bandwidth (B_f) At the interface queue level, the monitor observes the backlogged traffic (q_f). At the routing level, HELLO messages communicate the local queue information to its neighbors (or AP in the centralized case).

The measurement-based bandwidth estimation is based on the approach presented in [9]. It measures the *achievable* bandwidth of each wireless link based on its historical data transmission results.

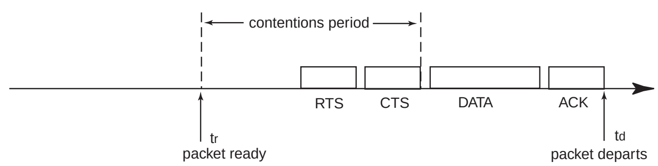


Fig. 6. Measurement-based bandwidth estimation.

As shown in Fig. 6, under the IEEE 802.11 MAC protocol, at time t_r, when a packet from a particular wireless link becomes the head-of-line packet (*i.e.*, the first packet waiting to be transmitted), we claim that the packet is *ready*. At time t_d, when the link layer acknowledgment is received, the packet *departs*. The transmission delay of this packet is then given as $t_d - t_r$, which includes a contention period. The contention period indicates the channel bandwidth used by packet transmissions of other wireless links within the interference range. The achievable bandwidth observed by this wireless link is then calculated as $\frac{z}{t_d - t_r}$, where z is the size of the packet. To achieve more accurate measurement results, we use a window of w packets to conduct the bandwidth estimation, *i.e.*, the bandwidth is estimated as $\frac{w \cdot z}{\sum_{i=1}^{w} t_d^i - t_r^i}$. The measurement-based bandwidth estimation takes into account the effect of physical layer interference and the inefficiency of MAC protocols, as it is based on the *scheduling results* of packet transmissions.

To get the transmit bit rate B_f of each wireless node, we use the software library *iwlib* developed by HP Lab. In particular, function *iw_sockets_open* returns a raw socket descriptor to the wireless driver at the kernel. And function *iw_print_bitrate* is used to get the instantaneous channel bit rate used by the current wireless adaptor.

Queue length monitor is implemented as a kernel module. It monitors the instantaneous queue length and provides such information to the user space. To get the instantaneous queue length, this module hooks two kernel queue management routines with our functions. In particular, it first retrieves the wireless device handler[2], and its queue discipline member *qdisc*. Then it replaces the function *enqueue* and *dequeue* of *qdisc* with two new functions that monitor the queue length and its changes. To provide the information of queue length to the user space, this module uses an *inode* device/file *queuelen*. The module also hooks up two new file handlers *dread* and *dwrite*, which operate over the system memory instead of disk file. This approach provides low-overhead kernel and user space communication.

V. Experiment Result

To validate the performance of our joint flow control and queue management solution and evaluate our system implementation, we conduct experiment over a wireless network testbed. In our experiment testbed, the wireless nodes are IBM T42 and G41 laptops with IEEE 802.11b Orinoco wireless adaptors. Each node uses Linux Fedora system with kernel version 2.6.5. The wireless network is configured in ad hoc demo mode using channel 6.

A. Base Scenario

We first study the basic behavior of our algorithm. In the experiment, four wireless nodes in the network are all within the transmission range of each other; two flows with the same bit rate start to transmit at different time instances. The experiment result is shown in Fig. 7.

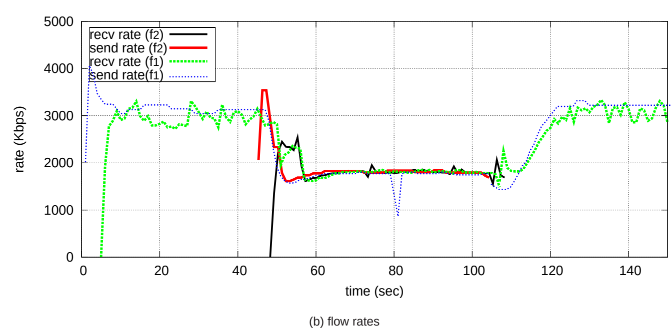


Fig. 7. Basic Scenario.

This result shows that: (1) the instantaneous sending rate and receiving rate converges even when traffic dynamically joins and departs the network. The time for convergence is within 10 seconds; (2) At equilibrium, the sending rates and throughput of both flows closely match, which means both flows share the wireless channel fairly.

B. Multi-rate scenario

We proceed to evaluate the performance of our algorithm in multi-rate wireless networks. The first experiment is conducted on a simple topology with one flow sending between two laptops. In the experiment, we manually set the bit rate of

[2]The wireless adaptor device in the Linux system is usually configured to "eth1".

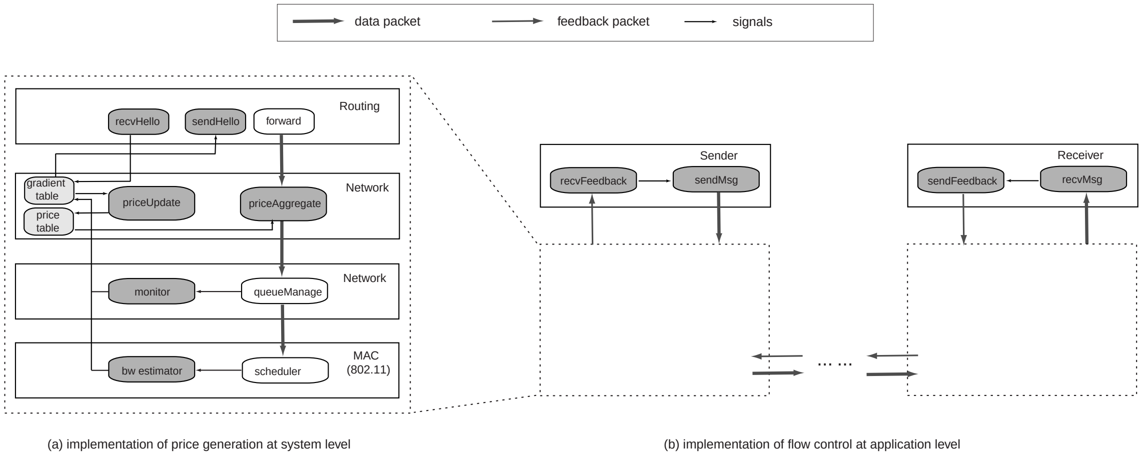


Fig. 5. Software Architecture for Joint Flow Control and Active Queue Management.

the wireless node *fixed* at different levels (in the sequence of 2M, 1M, 11M, and 5.5Mbps). The instantaneous sending and receiving rates of this flow are shown in Fig. 8. From the result, we see that our algorithm quickly adapts to the channel bit rate adjustment, and converges to the new equilibrium rate allocations within 10 seconds. In the second experiment, we set the channel bit rate of the wireless node to *automatic adaptation* mode. In this mode, the channel bit rate will be automatically adjusted based on the channel condition. In the experiment, we move the wireless node to create a dynamic channel condition, so that the bit rate will be adjusted accordingly. The result is plotted in Fig. 9. From the figure, we have similar observation that our algorithm quickly responds to the channel bit rate changes.

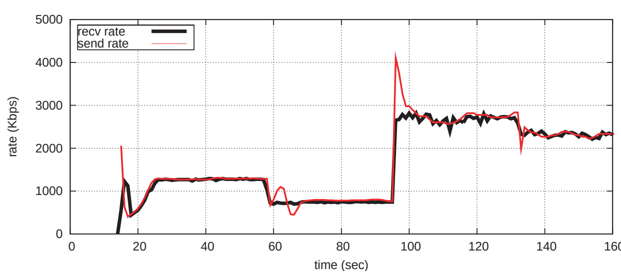


Fig. 8. Multi-rate scenario with one flow.

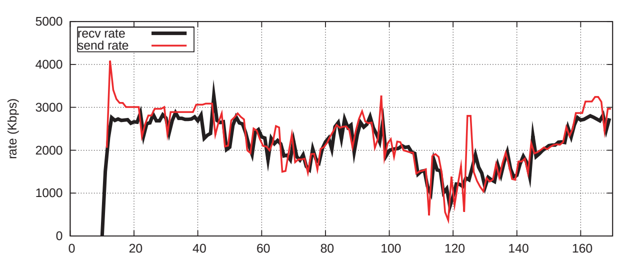


Fig. 9. Multi-rate scenario (mobile).

Now we experiment on a network with two flows between four laptops (the same as in the base scenario). In this experiment, the channel bit rate of flow 1 is fixed at 11Mbps, while the bit rate of flow 2 is adjusted manually in the sequence of 11M, 5.5M, and 2Mbps. The experiment result is shown in Fig. 10. From the result, we have the following observations. (1) The sending and receiving rates of both flows converge within 10 second after the bit rate adjustment of flow 2; (2) At equilibrium, when both flow 1 and 2 have the same channel bit rate, these two flows share the same throughput. When their bit rates are different, the throughput of these two flows are different. Moreover, their throughput ratio follows the ratio of the bit rates. This is a significant different result from the TCP behavior in multi-rate wireless networks shown in Fig. 2. Our experiment shows that our joint solution of flow control and channel-aware active queue management well addresses the TCP performance anomaly issue, improves the channel resource utilization, and provides proportional fair rate allocation to the contending flows in multi-rate wireless networks.

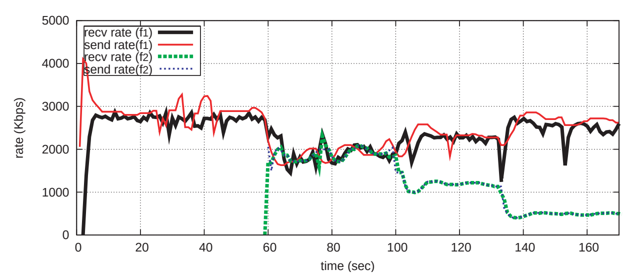


Fig. 10. Multi-rate scenario with two flows.

VI. Related Work

We evaluate and highlight our original contributions in light of previous related work.

Fairness and its tradeoff between channel utilization in wireless network has been studied extensively in the existing literature [10], [11], [12]. However, most of these solutions involves changes to the scheduling algorithm at the MAC layer. This is impractical given the wide deployment of IEEE 802.11 standard and the fact that MAC scheduling algorithm is implemented in the firmware of wireless adaptors. Moreover, the rate diversity problem has not been considered in the previous work. Our work addresses the fairness and channel utilization issue at the flow level and employs a joint flow control and active queue management scheme, which involves no change to the underlying MAC protocols. And we show that our approach can be implemented in the open source Linux system.

There are recent studies on channel time fairness [1], [2]. This paper is different from and enhances the above work in the following two aspects. First, it presents a theoretical foundation for channel time fairness and shows that proportional channel time fairness maximizes the aggregated utility of all flows in a multi-rate wireless network. Second, our approach presents a distributed solution which can be easily extended for multihop wireless networks.

The problem of optimal and fair resource allocation has been extensively studied in the context of wireline networks. Among these works, optimization-based flow control and active queue management has been shown to be an effective approach to achieve distributed solution for rate allocation (*e.g.,* [3], [13], [8], [14]). The optimization framework of our work is similar to [3], [8], [13], which reflects the relation of the demand and the supply of resources. Nevertheless, the fundamental differences in contention models between wireless and wireline networks deserve a fresh treatment to this topic. As we have emphasized, these resource allocation strategies employed in the wireline network may not be applied directly in the context of wireless networks due to the unique characteristics of the shared wireless channel. This work also enhances our previous work on resource allocation in wireless networks [4] by considering the rate diversity phenomenon and providing a Linux-based system implementation.

VII. Concluding Remarks

This paper investigates the problem of TCP performance anomaly issue over multi-rate wireless networks. It presents an optimization-based framework for flow control in multi-rate wireless networks. This framework provides analytical insight to the performance anomaly problem of TCP and establishes a theoretical foundation for a joint flow control and active queue management scheme that solves this problem. The presented active queue management scheme operates based on channel conditions as well as queue lengths. Testbed experiments are conducted on a Linux-based system implementation. The results show that our approach well addresses the TCP performance anomaly issue, improves the channel resource utilization, and provides proportional fair rate allocation to the contending flows in multi-rate wireless networks.

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